

INITIATION OF DETONATION BY INCIDENT SHOCK WAVES  
IN HYDROGEN-OXYGEN-ARGON MIXTURES

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INTRODUCTION

The steps involved in the initiation of detonation by incident shock waves have been outlined by Strehlow and Cohen (1). In their words, "An exothermic reaction occurring in a small region of a flowing gas causes an increase in the local pressure .... Since this region is subsonic the pressure increase will propagate to the front and increase the velocity of the front, thereby increasing the temperature of the next element of gas heated by shock compression. This process is self-accelerating and in general a steady-state wave will not be obtained until the wave is traveling at or above the Chapman-Jouguet velocity for the mixture."

For dilute hydrogen-oxygen-argon mixtures, ignition induction times ranging from microseconds to milliseconds can be obtained over a range of temperatures (2,3). In a shock tube equipped with several velocity-measuring stations, we have shock-heated such mixtures to temperatures at which induction times are a few milliseconds long, and observed in considerable detail the process by which the reaction wave, initiated several meters behind the shock wave, overtakes and couples with the shock wave.

Earlier measurements (4,5,6) have indicated the increase in shock velocity due to coupling of the reaction to the shock wave, but have not shown many of the details of the process. Strehlow and co-workers (1,7,8) have made extensive studies of initiation of exothermic reactions behind reflected shock waves. Oppenheim, Laderman, and Urtiew (9,10) have reported extensive studies on the initiation of detonations in gaseous mixtures where the ignition source was a spark, a flame, or a hot wire.

### EXPERIMENTAL

A square shock tube 7.62 cm. on a side was used. This had a driver gas section 1.83 meters long and a sample gas section 6.10 meters long. Diaphragms were of 1.22 mm. thick aluminum, scribed diagonally so that, when they burst, four triangular sections would fold back, one along each side of the tube. Air was used as driver gas.

When a run was made, the air was added to the driver section at the desired pressure (below the bursting pressure of the diaphragm), then the diaphragm was ruptured by a plunger. This permitted close control (about 0.5%) over the driver gas pressure.

The sample gas section was instrumented with thin-film platinum heat transfer gauges for velocity and heat transfer measurements, and with SLM Model 603 piezoelectric gauges (Kistler Instrument Corporation, Clarence, New York) for pressure measurements. The positions of these gauges with respect to the diaphragm are listed in Table I.

Table I

Positions of Gauges with Respect to Shock-Tube Diaphragm

Gauge	Distance Downstream from Diaphragm, Meters
Heat transfer No. 1	3.2004
Heat transfer No. 2	3.8100
Heat transfer No. 3	4.4196
Heat transfer No. 4	4.6482
SLM No. 1	4.6991
Heat transfer No. 13	4.6991
Heat transfer No. 5	4.8006
Heat transfer No. 6	4.9022
SLM No. 2	4.9530
Heat transfer No. 7	5.0038
Heat transfer No. 8	5.1054
Heat transfer No. 9	5.2070
Heat transfer No. 10	5.3086
Heat transfer No. 11	5.3594
Heat transfer No. 12	5.9690

Heat transfer gauges 1, 2, and 3, and SIM gauge 1 were mounted on the side of the tube; the others were on the top. Heat transfer gauge 13 was used to measure the rate of heat transfer from the gas to the wall. The time base for all velocity measurements was a Tektronix Model 180A time-mark generator. Outputs from the piezoelectric gauges were fed into charge amplifiers, then recorded using a

Tektronix Model 555 oscilloscope. The piezoelectric gauges were calibrated statically against a precision laboratory pressure gauge.

### RESULTS

In the temperature range under study, the induction time for ignition of a hydrogen-oxygen-argon mixture varies rapidly with temperature. Accordingly, a good many experiments were necessary to determine the conditions needed to bring about coupling of the reaction and shock waves in the right part of the tube. This point is illustrated by the data of Figure 1, which apply to a gas mixture containing approximately 4%  $H_2$  and 2%  $O_2$  by volume in argon.

With sample pressures above about 0.086 atm., the variation of shock speed with sample pressure is as one would expect when no chemical reaction is occurring. In the sample pressure range of 0.082 to 0.086 atm., the shock speed reaches a high value as the reaction wave catches up to the incident wave. For lower sample pressures, the reaction has coupled to the shock wave before the wave reached the measuring station. The effects of small differences in initial pressure, and of other minor variables such as the speed of diaphragm rupture, are shown by the three different shock speeds measured for presumably identical runs at 0.084 atm. Complete data for these three runs show that in one case the peak shock speed occurred before heat transfer gauge 8, in one case between gauges 8 and 9, and in the other case after gauge 9.

A complete set of data for the run that gave the highest velocity in Figure 1 is shown in Figures 2 and 3. The data of Figure 3 have been redrawn from the original oscilloscope records in order to have the same time scale for all the records, and the same pressure scale for the pressure records.

Similar sets of data were obtained for gas mixtures containing approximately 6%  $H_2$  and 3%  $O_2$ , and 8%  $H_2$ , and 4%  $O_2$ . For these mixtures, of course, the energy release by chemical reaction was greater than for the first mixture studied, and the pressure and velocity effects correspondingly more pronounced. Data for a run with the more concentrated mixture are shown in Figures 4 and 5.

### DISCUSSION

The data presented in Figures 2 to 5 can best be related by drawing wave diagrams for each experiment. Sufficient data are available to draw reasonably complete wave diagrams, which are given in Figures 6 and 7.

The procedure for drawing Figure 6 was as follows: From Figures 1 and 2 it can be seen that the first velocity measurement of Figure 2 corresponds to a shock wave unaffected by chemical reaction.

Therefore, the shock velocity from the diaphragm to heat transfer gauge 2 will be constant (neglecting diaphragm opening effects and attenuation) at a velocity of approximately 870 meters/sec. (The shock speed that is calculated from the pressures of sample and driver gas, by means of Markstein's graphical method (11), is 880 meters/sec., in close agreement.) If the diaphragm opening time is taken as 0, the incident shock wave will reach heat transfer gauge 2 in 4.38 milliseconds (point A of Figure 6). From this point on, the times to reach various points on the tube are given directly by the data.

It is evident from the slow rise in shock speed between 3.5 and 4.9 meters (Figure 2) that the chemical reaction first produces a gentle pressure wave that travels through the shock-heated gas with velocity  $u + a$ , where  $u$  is the flow velocity behind the shock wave (551 meters/sec) and  $a$  is the speed of sound in the heated gas (557 meters/sec). Accordingly, a characteristic line with  $u + a$ , of 1108 meters/sec. can be drawn back from Point A, to represent the path of this first pressure wave that communicates energy from the reaction to the shock wave.

The origin of this wave is undoubtedly near the driver-sample interface, at which is located the part of the gas sample that was heated first (point B of Figure 6). It is apparent that the ignition induction time was about 2 milliseconds, or a little less if it is considered that some of the sample next to the diaphragm will be cooled by driver gas and not react. The calculated temperature behind the incident shock wave is 880°K., and the pressure 0.68 atm.

From Point B the reaction front first appears as a line parallel to the incident shock wave. That is, once the gas has been heated for 2 milliseconds, it starts to react. However, as pressure waves from the reaction increase the incident shock speed, they also increase  $u$  and  $a$  behind the shock wave. This means, first, that the ignition induction times of successive elements of the gas become shorter, so that the velocity of the reaction wave exceeds that of the shock wave, and second, that pressure waves can catch up with waves sent out previously, thereby generating a shock wave. The formation of this second shock wave is shown in Figure 3. It was just beginning to form as it passed SIM gauge 1, and was better formed as it passed SIM gauge 2. The average velocity in the interval, 1340 meters/sec., is just a little greater than  $u + a$ , as one would expect for a weak shock wave. Once the two waves coalesce, the temperature behind the wave is close to 2000°K., at which temperature the induction time is about 20 microseconds (2,3). By this time, then, the reaction wave is close behind the shock wave, as shown in Figure 6.

The wave diagram for the more concentrated gas mixture, Figure 7, is similar in many ways to Figure 6. One notable difference is that the first evidence of chemical reaction to reach the incident shock wave was a well-developed second shock wave, of velocity

2080 meters/sec., which had overtaken and assimilated weak pressure waves sent out earlier when reaction started. The fact that the shock wave had the same shape at the two pressure measuring stations suggests that this is a detonation wave in the gas which had been preheated to 830°K., compressed to 0.79 atm., and accelerated to 555 meters/sec. by the incident shock wave. A calculation of the detonation properties made by standard methods (12) gave the following data, which are compared to the experimental measurements.

<u>Property</u>	<u>Observed</u>	<u>Calculated</u>
Detonation velocity relative to unreacted gas	1,525 meters/sec.	1,465 meters/sec.
Detonation pressure	4.6 atmospheres	5.7 atmospheres
Temperature after reaction	-	2,700°K

The agreement, while not highly accurate, is sufficiently close to confirm the identity of the wave.

The data for this run do not indicate where the detonation wave started, nor where it caught up with the first pressure wave from the reaction zone. Two extreme cases can be considered.

1. The detonation wave formed as soon as reaction started, so a line drawn back from the intersection of the detonation wave with the incident shock wave (Point C of Figure 7) with a slope corresponding to 2080 meters/sec intersects the driver-sample interface at the point of initial reaction, at a time of 4.9 milliseconds.
2. The detonation wave overtook the first pressure wave from the reaction just before the latter reached SIM gauge 1, so that a characteristic drawn back from the detonation wave at this point, with a slope corresponding to a  $u + a$  of 1110 meters/sec., intersects the driver-sample interface at the point of initial reaction, at a time of 3.2 milliseconds. The wave diagram has actually been drawn half-way between these two extremes, on the assumption that the induction time was 4.0 milliseconds.

The fact that the speed of the incident shock wave goes through a maximum value as the reaction wave couples to it, than later decreases somewhat, is to be expected from the mechanism of the process. Since no reaction occurs during the first few milliseconds, the rate of energy release by chemical reaction reaches a transient maximum value significantly above the normal rate as the reaction wave catches up with the shock wave.

More quantitatively, the velocity of a shock wave with heat release can be calculated, and the calculation gives a value lower than the maximum velocity of Figure 2. We have used Markstein's graphical method (11) in these calculations also. With reference to the experimental conditions of Figure 2, if the induction time was zero an ordinary-looking shock wave would be obtained, with a velocity of 1110 meters/sec., a pressure of 0.75 atm., and a temperature of 1460°K (compared to calculate values of 880 meters/sec., 0.71 atm and 890°K when no reaction occurs). The shock velocity of 1110 meters/sec. would be reached eventually in our experiment with an induction time, if the tube were long enough and attenuation could be neglected. Once this steady situation was reached the pressure would be uniform from the shock front to the driver gas expansion region.

When the same type of calculation is made for the gas mixture containing more hydrogen and oxygen, corresponding to Figures 4 and 5, it is found that the air driver is not capable of maintaining sufficient flow velocity to keep the pressure constant behind the incident shock wave when reaction occurs. The final steady state wave would, therefore, have an appearance between a shock and an ordinary detonation wave, with some drop in pressure, temperature and flow velocity behind the shock front.

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REFERENCES

1. R.A. Strehlow and A. Cohen      Phys. Fluids 5, 97 (1962).
2. G.L. Schott and J.L. Kinsey.    J.Chem. Phys. 29, 1177 (1958).
3. G.B. Skinner and G.H. Ringrose. J.Chem. Phys. 42, 2190 (1965).
4. J.A. Fay, Fourth Symposium (International) on Combustion, 1952, p. 501.
5. M. Steinberg and W.E. Kaskan. Fifth Symposium (International) on Combustion, 1954, p. 664.
6. F.E. Belles and J.G. Ehlers. Am. Rocket Soc. J. 32, 215 (1962).
7. R.A. Strehlow and H.B. Dynner, AIAA Journal 1, 591 (1963).
8. R.B. Gilbert and R.A. Strehlow, AIAA Journal 4, 1777 (1966).
9. A.J. Laderman and A.K. Oppenheim, Proc. Roy. Soc. A268, 153(1962).
10. P.A. Urtiew and A.K. Oppenheim, Proc. Roy. Soc. A295, 13(1966).
11. G.H. Markstein. Am. Rocket Soc. J. 29, 588 (1959).
12. B. Lewis and G. von Elbe. Combustion, Flames, and Explosions of Gases, Second Edition, New York, Academic Press, Inc., 1961, p. 524.

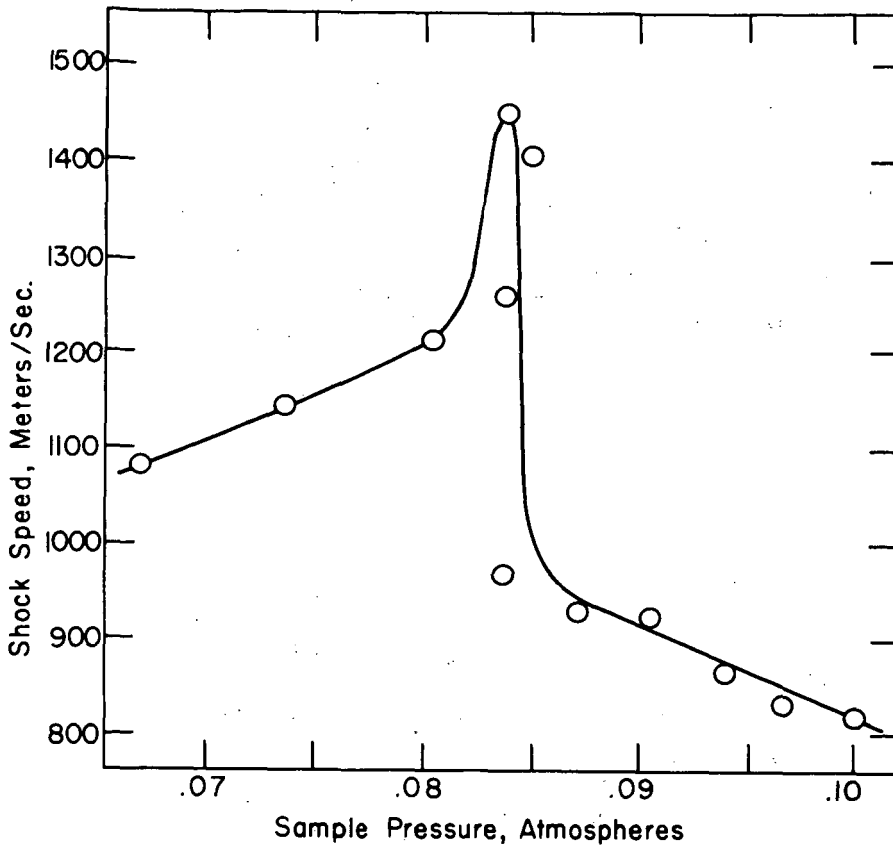


Figure 1. Incident shock speeds measured between heat transfer gauges 8 and 9 for a gas mixture containing 4.33%  $H_2$  and 1.88%  $O_2$  by volume in argon. Driver gas 17.0 atm. of air.



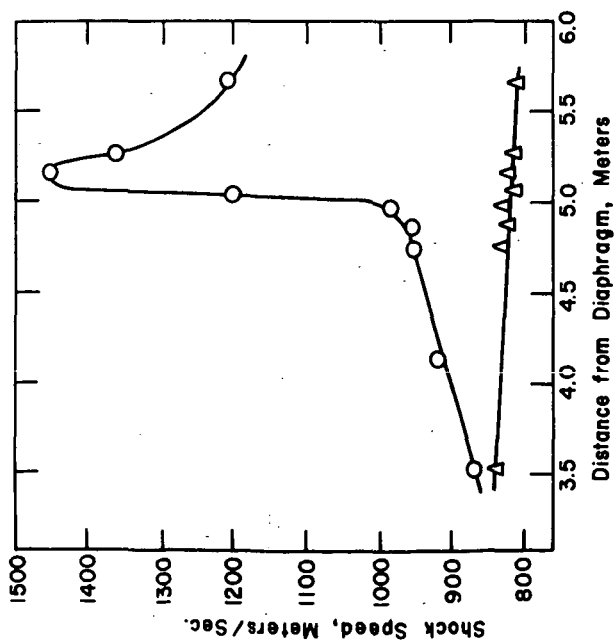


Figure 2. Incident shock speeds measured at different positions along the tube for a gas mixture containing 4.33%  $H_2$  and 1.88%  $O_2$  by volume in argon. Driver gas 17.0 atm. of air.  $\circ$  Sample pressure 0.084 atm.;  $\Delta$  Sample pressure 0.100 atm., for comparison

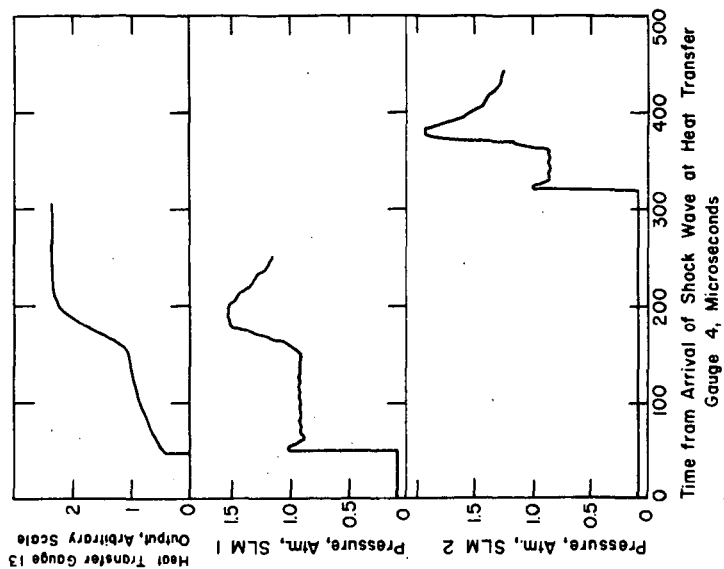


Figure 3. Pressure and heat transfer records for the same experiment as Figure 2 (sample pressure 0.084 atm.).

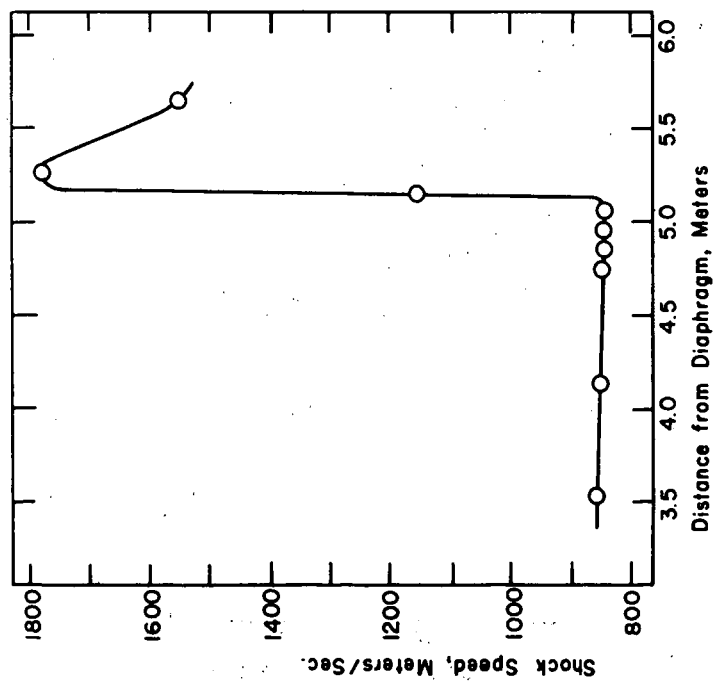


Figure 4. Incident shock speeds measured at different positions along the tube for a gas mixture containing 7.82%  $H_2$  and 4.46%  $O_2$  by volume in argon. Sample pressure 0.100 atm., driver gas 17.0 atm. of air.

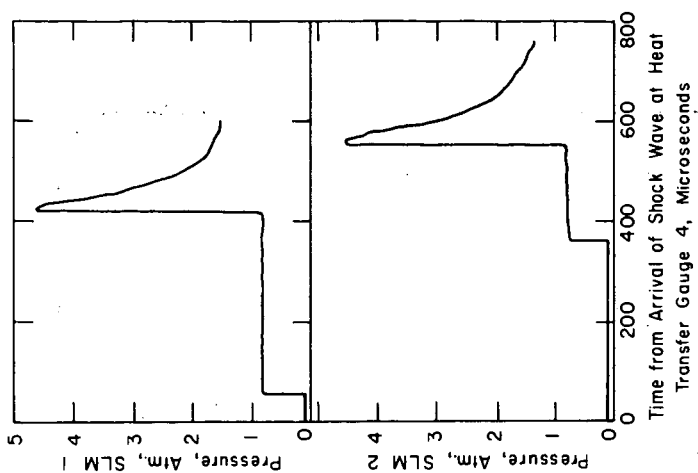


Figure 5. Pressure gauge records for the same experiment as Figure 4.

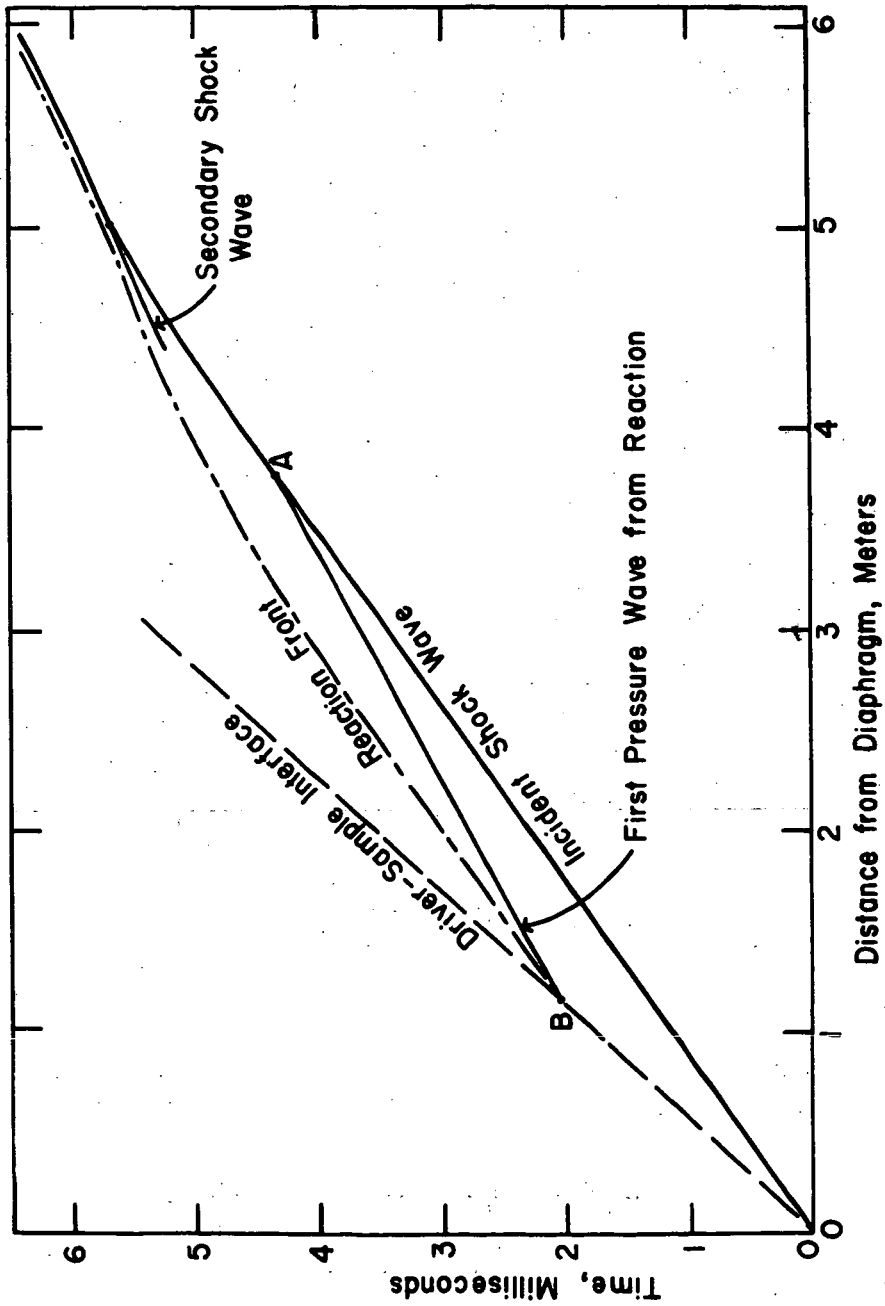


Figure 6. Wave diagram drawn from data of Figures 2 and 3.

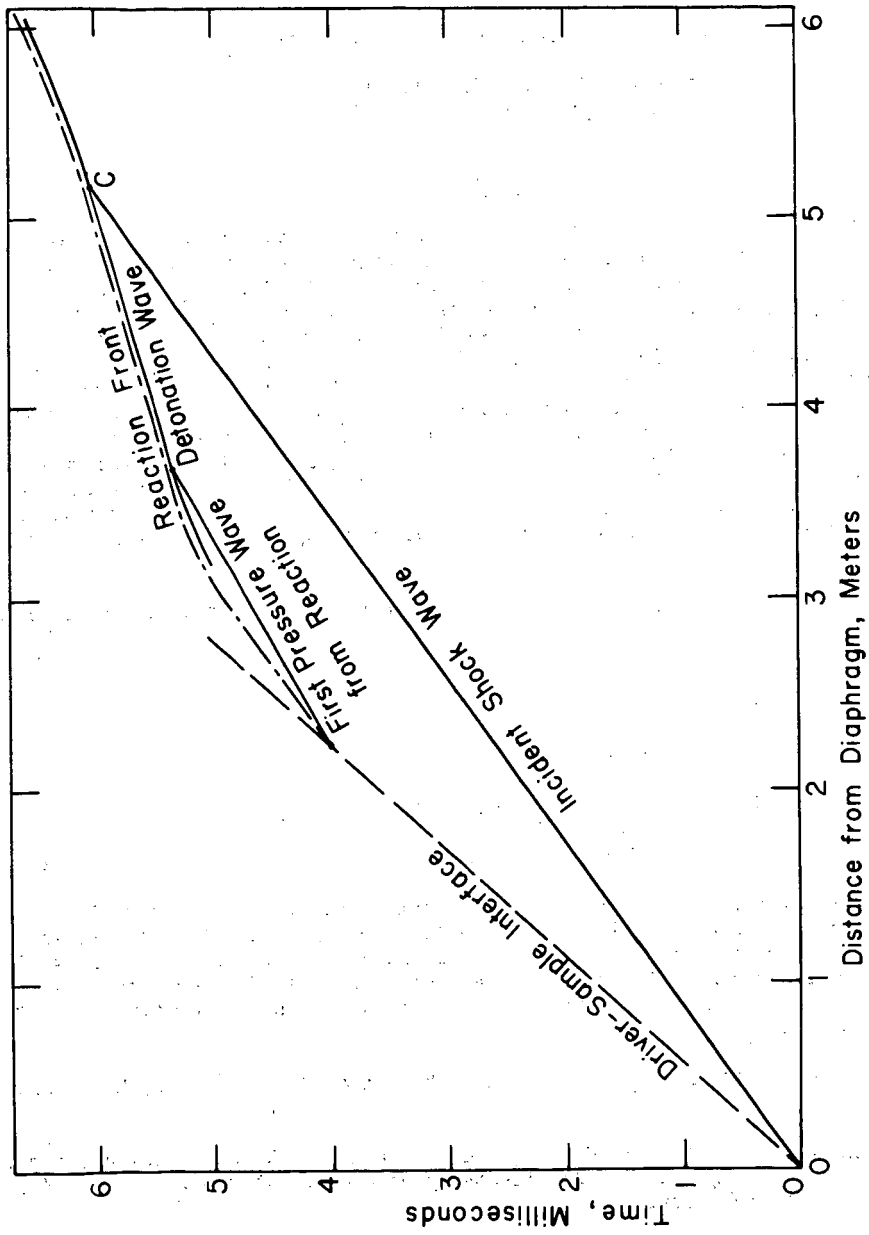


Figure 7. Wave diagram drawn from data of Figures 4 and 5.